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REFLECTIONS ON THE IMPACT OF FIX TYPE AND
ACCURACY ON TROPICAL CYCLONE TRACK FORECASTS

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Abstract

The decision to terminate aircraft reconnaissance of western North Pacific tropical cyclones has prompted discussion of the impact of the different types of center positioning on the accuracy of track forecasts. A review is given first of the recent studies on the accuracy of position and intensity estimates from satellite images only. Dispersion in the satellite-based position estimates is primarily a function of the intensity, with larger differences for weaker storms. Conversely, dispersion in the intensity estimates increases with tropical cyclone intensity. Evaluations of the accuracy of operationally-analyzed positions from satellite imagery suggest that the amount of supporting information that is available to the satellite analyst has a noticeable influence. The uncertainty in our knowledge of the actual storm center from independent sources makes determination of absolute accuracy difficult.

Various evaluations of the effect of center fix accuracy on track forecasts by empirical, statistical and dynamical models also are reviewed. A large impact of initial position uncertainty has been shown in the CLImatology and PERsistence (CLIPER) technique. However, if the erroneous fix is blended with other information to derive a smoothed representation of the past track, the impact on CLIPER forecasts is greatly reduced. Thus, the conclusion on potential impact is dependent on the operational procedures or the context in which the erroneous fix is utilized. In the dynamical models, the initial position uncertainty primarily affects the short-term forecast. Since these models are initialized with large-scale fields, the dispersion due to initial position uncertainty does not grow with time in most cases. However, very large differences in track can occur in individual cases. Two studies of the impact of aircraft reconnaissance on official track forecast accuracy suggest the significant positive effects are confined to recurving storms in the 20° to 35° lat. band.

1. Introduction

The termination of aircraft reconnaissance in western North Pacific tropical cyclones during August 1987 has led to much discussion of the potential impact of the aircraft reconnaissance and of the accuracy of satellite-based estimates. At the 41st Interdepartmental Hurricane Conference, an Ad Hoc Group for Tropical Cyclone Studies was tasked to:

> (i) Investigate the state of satellite tropical cyclone interpretation accuracies; plan, coordinate and conduct a study of operational accuracies of satellite-based tropical cyclone estimates of positions, intensities and wind fields; and prepare a report of the investigation.
>
> (ii) Investigate the contribution of airborne weather reconnaissance in tropical cyclone forecasting; guide a study of tropical cyclone forecast accuracy based on non-airborne weather reconnaissance data; work in conjunction with the study on satellite tropical cyclone interpretation accuracies; and prepare a report of the investigation.

The Office of the Federal Coordinator for Meteorological Services and Supporting Research coordinated the study. Their recent publication (FCM-R11-1988) provides the results of the first task as well as the first portion of the second task.

In Section 2 of this report, the three studies (Sheets and McAdie 1988; Mayfield _et_ _al_. 1988; Guard 1988) on accuracy of the satellite-based estimates in FCM-R11-1988 are reviewed briefly in relation to a study by Martin (1988). The third section of this report addresses the second task above. Studies of the effect of fix accuracy on track forecasts by empirical, statistical and dynamical models are reviewed. The study by Sheets (1988) in FCM-R11-1988 is compared with Martin (1988), who addresses the impact in the western North Pacific. Finally, some conclusions based on this review are offered in Section 4.

2. Review of recent TC fix accuracy studies

The perspective of this review is that of a person designing an objective warning position system (e.g., Curry et al. 1987) that uses all of the different observational platforms for fixing the tropical cyclone. The basic requirement is then to specify the "goodness" of each type of fix based on its expected accuracy. Consequently, the first question is: What have recent studies revealed as to the inherent scatter of satellite position or intensity estimates? As these studies have reconfirmed, the accuracies are strongly dependent on the intensity of the tropical cyclone. The second point to be addressed is the possible change in accuracy of the satellite-based estimates when the aircraft-based estimates are absent. That is, the accuracy estimates based on operationally-analyzed positions and intensities are a function of the combination of systems that were blended together to obtain the best possible warning position. Furthermore, the post-storm analysis of the "true" position and intensity of the tropical cyclone is affected by the combination of systems that were available. The final point is then to examine the operationally-based estimates of the various satellite accuracies in terms of the likely bias that coincident aircraft fixes might have introduced. Differences in polar-orbiting and geostationary satellites and between visible and infrared imagery also need to be examined.

a. Dispersion in satellite-based position estimates

Mayfield et al. (1988) have replicated an earlier study by Sheets and Grieman (1975) to evaluate the accuracy of tropical cyclone intensities and locations from satellite imagery only. This new study used the enhanced infrared imagery from geostationary satellites for 14 tropical cyclones in the eastern North Pacific. Seven analysts from the National Hurricane Center (NHC) and seven from the Satellite Analysis Branch of the National Environmental Satellite, Data and Information Service (NESDIS) estimated the positions and intensities at 6 h intervals from operationally obtained Unifax pictures. Since skilled analysts were examining the identical imagery, the comparison of the 14 estimates for each classification time provides a measure of the dispersion that might be expected from the Dvorak (1984) position and intensity technique.

A key conclusion of this (and the Sheets and Grieman) study is that the accuracy of the satellite-based position estimates is a strong function of the intensity of the tropical cyclone (Table 1; Fig. 1). The mean dispersion about the centroid for the 14 separate estimates is only 12 n mi for Hurricane Stage 3 and greater (maximum winds exceeding 96.4 kt), whereas the mean dispersion is 31 n mi for tropical depression or weaker stages (winds less than 34 kt). Also provided in Table 1 are the magnitudes in the position deviations to be expected in 50% and (largest) 10% of the cases when skilled analysts are estimating positions using recently developed techniques. For example, 10% of the weak storm estimates resulted in positions deviating by 62

Table 1 Deviations (n mi) among 14 satellite-based tropical cyclone positions relative to the centroid of the 14 positions. Columns labelled 50% and 10% indicate deviation values exceeded in 50% and 10% of the cases (Mayfield et al. 1988)

	Number of Cases	Mean	Std. Dev.	50%	10%
Trop. Depression Stage and Weaker Systems	1243	31	25	25	62
Tropical Storm Stage	2502	24	24	18	48
Hurricane Stage Category 1 and 2	1163	16	17	12	30
Hurricane Stage Category 3 and Greater	420	12	14	9	24

Table 2 Deviations (n mi) of AFGWC satellite-based tropical cyclone positions from those of the Eastern Pacific Hurricane Center (EPHC) or the National Hurricane Center for Atlantic Storms. Columns labelled 50% and 10% indicate deviation values exceeded in 50% and 10% of the cases (Sheets and McAdie 1988).

	Eastern Pacific				Atlantic			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. depressions	47	36	36	100	45	35	34	93
Trop. Storms	39	36	30	83	38	27	31	69
Hurricanes	27	17	20	53	28	20	23	55

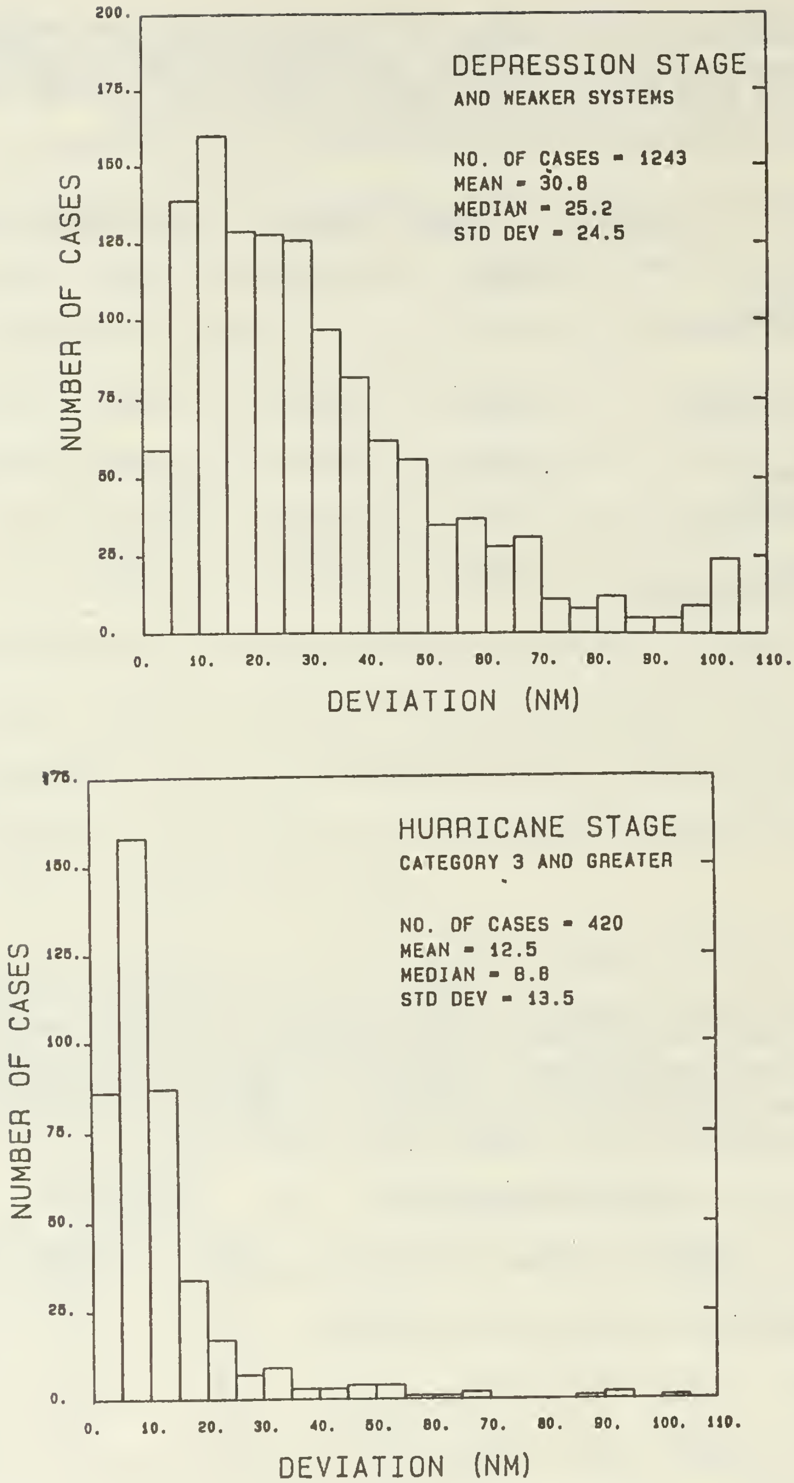

Fig. 1 Deviations (n mi) among 14 satellite-based tropical cyclone positions relative to the centroid of the 14 positions for (top) depression stage and (bottom) category 3 or greater hurricane stage with winds exceeding 96 kt (Mayfield et al. 1988).

n mi or greater (more than 1 degree latitude) and the largest 10% of the most severe tropical cyclone cases had deviations of 24 n mi. The conclusion is that the enhanced infrared geostationary satellite estimates of tropical cyclone positions have a high degree of consistency for intense stages, but the forecaster must expect rather large variability in the position estimates at weaker stages. Although this fact was known by forecasters, it did not always seem to be appreciated in recent discussions about the impact of eliminating aircraft reconnaissance.

Guard (1988) also conducted a controlled experiment in which four satellite analysts at the Air Force Global Weather Center (AFGWC) were given only polar orbiter imagery from the Defense Military Satellite Program (DMSP) and NOAA polar orbiters. Thus, the analysts had no synoptic data, no interaction with other analysts or forecasters to gain a consensus interpretation, no quality control from a senior analyst and no geostationary animation to support or confirm their polar orbiter imagery interpretation. The internal consistency was defined by Guard as the deviation of the estimates from the three less experienced analysts relative to the most experienced analyst (4 years). Given this different definition relative to the Mayfield et al. study, it is surprising that dispersion estimates for their tropical storm and more intense typhoon stages closely agree with the values in Table 1.

Guard also examined the possible errors due to gridding of the imagery. The high resolution of this DMSP and NOAA imagery allows a much improved gridding compared to the 1975 study.

Thus, this gridding error (~3-5 n mi) would not contribute significantly to the TC position error in 98% of the cases.

Martin (1988) examined internal consistency among operationally-derived estimates from different sites in the western North Pacific region. Included in this sample were 54% DMSP, 419% NOAA polar orbiters and 5% Geostationary Meteorological Satellite (GMS) images. The characteristic decrease in position consistency for weaker storms is well illustrated in Fig. 2. Although these estimates are from a different tropical cyclone basin than in Table 1, the larger scatter for the operational estimates in weaker storms (Current Intensity 1 and 2 in Fig. 2) might be expected as satellite analysts change frequently at military sites. The operational analysts had only visible imagery in 13% of the situations, only infrared imagery in 35% of the cases and used both types in 52% of the estimates. Without stratifying by intensity, the mean differences among sites were 29, 32 and 26 n mi respectively, with corresponding reductions in standard deviations for the visible only and the combined visible and infrared situations. In particular, the daytime operationally-derived differences among the sites were 29 n mi, whereas the differences increased to 32 n mi at night.

Another check of internal consistency of satellite-derived positions was provided by Sheets and McAdie (1988). They compared (Table 2) the operationally-determined positions by analysts at AFGWC with those from the Eastern Pacific Hurricane

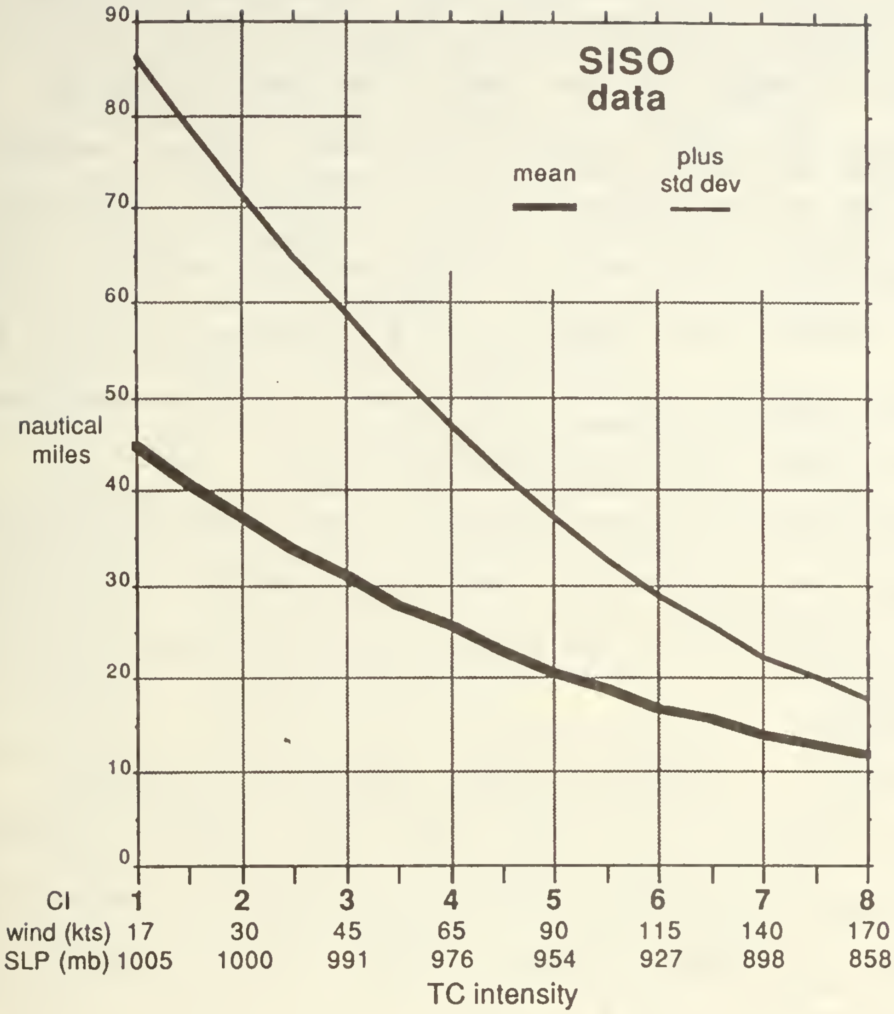

Fig. 2 Mean (heavy solid) plus one standard deviation (solid) of position differences between simultaneous independent satellite observations (SISO) in western North Pacific as a function of cyclone intensity (Martin 1988).

Center (EPHC) and the National Hurricane Center (NHC) for Atlantic tropical cyclones. The latter two centers utilize geostationary imagery of the type in the Mayfield et al. (1988) study whereas the AFGWC analysts use polar orbiter imagery. The distributions of the differences as a function of tropical cyclone intensity are similar for the Eastern Pacific and the Atlantic. However, the operational differences in Table 2 are considerably larger than the single-source differences among 14 analysts in Table 1 from the Mayfield study. That is, operational satellite-based estimates from different centers do not approach the consistency standard suggested by the rather controlled conditions in the Mayfield et al. (1988) or Guard (1988) studies.

b. Dispersion in satellite-based intensity estimates

The Mayfield et al. (1988) study also examined internal consistency of the tropical cyclone intensity estimates from geostationary enhanced infrared imagery. The standard deviations for the 14 analysts were 4.3, 9.0. 10.7 and 12.0 kt for the depression, storm, weak hurricane and strong hurricane stages respectively. The dispersion is small for the depression stage because the only possible choices in the Dvorak technique are 25 and 30 kt.

The dispersion among the four AFGWC analysts using only polar orbiter imagery in the Guard (1988) test was expressed in terms of Current Intensity (CI) numbers, which must be converted to wind speeds for comparison with the Mayfield study. Even allowing for the conversion uncertainties, the AFGWC analysts had larger standard deviations. This appears to be attributable to a lack of experience on the part of some of the analysts, who tended to underestimate the strength of the storms. It is emphasized that these studies only demonstrate the internal consistency among analysts applying the Dvorak technique to a single type of satellite imagery. As will be shown later, these values do not indicate actual accuracies.

Martin (1988) also summarized intensity (central sea-level pressure) differences among the different operational sites. The mean difference was only 3 mb and only 10% of the 1640 estimates differed by more than 11 mb. It is again emphasized that these values measure internal consistency rather than absolute accuracy. The distribution of these intensity differences as a function of tropical cyclone intensity is shown in Fig. 3. Although these differences are expressed in millibars rather than in wind speeds as in the Mayfield et al. (1988) study, a similar distribution is found of small differences for weak storms and decreasing consistency for stronger storms. This distribution is expected in view of the limited options for CI values equal to 1 or 2 (see SLP values at bottom of Fig. 3), and the increased variability in SLP inherent in larger CI values.

Another study of internal consistency among operational satellite-based intensity estimates was provided by Sheets and McAdie (1988). Intensity deviations between the AFGWC estimates from polar orbiter imagery and that from geostationary imagery used by EPHC and NHC were expressed in terms of CI values. The standard deviations of the CI were about 0.5, about 0.7 and 0.6

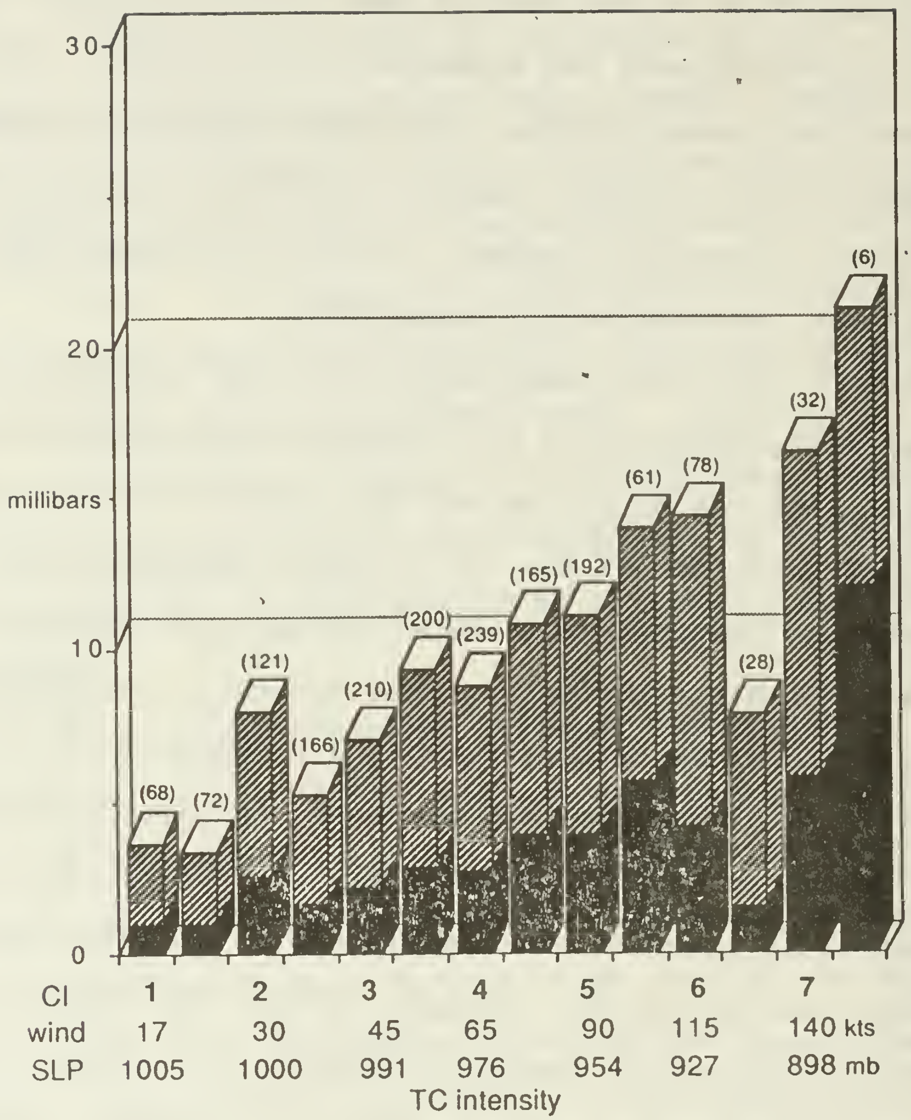

Fig. 3 Differences in tropical cyclone (TC) intensity estimates among simultaneous independent satellite observations as a function of storm intensity. Mean (black) plus one standard deviation (strippling) is indicated for the number of cases shown in parentheses (Martin 1988).

for the tropical depression, tropical storm and hurricane stages respectively. These values, which are roughly comparable to the Guard (1988) test, are difficult to compare directly with the Mayfield et al. (1988) and Martin (1988) studies, because of the nonlinearity in the conversion between CI number and maximum wind speed. However, a trend of decreasing internal consistency with increasing tropical cyclone intensity is common to the four studies.

c. Accuracy measures from operationally-analyzed estimates

The above internal consistency studies of satellite-based tropical cyclone positions and intensities demonstrate that the user must take into account the storm intensity. Specifically, internal consistency in position (intensity) estimates increases (decreases) from the tropical depression stage to the most intense hurricane stage. The dispersion of operationally-derived estimates with the Dvorak technique from different satellite platforms (DMSP or NOAA polar orbiters versus geostationary) is larger than the dispersion achieved in a large sample of cases by 14 expert analysts (Mayfield et al. 1988). These studies were reviewed separately to establish the internal consistency of satellite-based estimates prior to addressing the more difficult question of "absolute" accuracy.

Two issues arise in establishing the accuracy of satellite-based estimates. The first issue is that actual storm positions or intensities often are not known independently of the satellite estimates. Although a post-storm analysis of all fixes is done carefully, two centers (individuals) may differ considerably in "best-track" positions (~ 40 km according to Bell, 1981) and intensities. Since the satellite estimates are used in the post-storm analysis, the true accuracies of the satellite-based positions or intensities can not be determined. It is shown below that the post-storm values will tend toward the satellite estimates if no independent information is available. In these situations, a biased view of the accuracy of the satellite estimates will be obtained from these post-storm values.

A second issue in using operationally-analyzed satellite estimates is that non-satellite intelligence (aircraft fixes, extrapolation of working best-track positions, etc.) may have been used in interpreting the satellite imagery to provide the best possible estimate. In these cases, the accuracy is not simply that of the satellite estimate, but of the entire analysis system. Now that aircraft reconnaissance has been withdrawn from the western North Pacific, are the accuracies based on the satellite estimates prior to this time still valid? Since the answer is almost certainly no, what accuracies should be specified in an objective technique for tropical cyclone positioning?

The approach here will be to review the recent studies of satellite-based estimates and then to point out the evidence related to the two issues above. It will be left to the reader to draw conclusions or to make the proper interpretations.

d. Operationally-analyzed positions from satellite data

Sheets and McAdie (1988) compare the satellite-based estimates in the Atlantic basin during 1981-86 to the Best Track determined from all sources of data (including these satellite estimates). The Atlantic estimates by NHC (right side, top in Table 3) are from geostationary imagery, whereas the AFGWC estimates (bottom of Table 3) are from polar orbiter imagery. The NHC deviations from best track are considerably smaller than the AFGWC estimates. Sheets and McAdie suggest that the better agreement may be due to more consistent geostationary navigation and the extra information from animation of geostationary imagery that is not possible from polar orbiter imagery. However, the resolution of the polar orbiter imagery is better, especially for night-time imagery.

Two other features of the Atlantic comparisons in Table 3 are worthy of note. First, the AFGWC position deviations from best track values for tropical depressions are significantly smaller than the satellite-to-satellite consistency values in Table 2. Second, the larger position variability for tropical storms and tropical depressions relative to the hurricane stage that characterized all the internal consistency studies in Section 2a above is not present in the NHC values. This is evidence that the NHC satellite analysts are interpreting the geostationary imagery for those weaker storms in terms of additional information, including aircraft reconnaissance. This aspect will be discussed further below.

Sheets and McAdie separate the NHC geostationary imagery estimates into visible and infrared categories (Table 4). The estimates from visible (infrared) imagery are consistently 3-4 n mi smaller (larger) than the overall mean values in Table 3. The

Table 3 Deviations (n mi) of EPHC, NHC and AFGWC satellite-based tropical cyclone positions relative to the corresponding best track positions. Columns labelled 50% and 10% indicate deviation values exceeded by 50% and 10% of the cases (Sheets and McAdie 1988).

GEOSYNCHRONOUS

	EPHC-Eastern Pacific				NHC-Atlantic			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. depressions	24	22	17	55	23	19	18	48
Trop. Storms	26	22	20	55	22	19	17	45
Hurricanes	14	12	11	28	19	19	14	38

AFGWC-Atlantic-POLAR ORBITER

	Mean	S.Dev.	50%	10%
Trop. Depressions	36	25	29	66
Tropical Storms	34	23	30	68
Hurricanes	26	17	22	54

Table 4 Deviations (n mi) of NHC satellite-based tropical cyclone positions relative to the best track positions for visible (daytime) and infrared imagery. Columns labelled 50% and 10% indicate deviation values exceeded by 50% and 10% of the cases (Sheets and McAdie 1988).

	VISIBLE SPECTRA				INFRARED SPECTRA			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. depressions	19	16	16	39	27	20	21	56
Trop. Storms	19	17	15	40	25	22	19	50
Hurricanes	16	14	13	32	22	23	15	49

deviations associated with the largest 10% values are correspondingly smaller (larger) for the visible (infrared) imagery relative to the overall means. Thus, the user must know whether visual or infrared imagery was used in the position estimate if the proper weighting factors are to be used in an objective positioning scheme.

As an alternative to the "incestuous" comparison with the best track positions that are influenced by the satellite estimates, Martin (1988) compares the satellite estimates with interpolated positions between adjacent aircraft fixes. Of his 7893 satellite observations, 4594 of them were within 3 h of an aircraft measurement. Nevertheless, this approach is open to criticisms regarding linear interpolation between successive aircraft positions (versus a smooth fit) and the implied assumption that the reconnaissance aircraft fixes are perfect. Consequently, Martin's estimates of satellite accuracies actually include an unknown scatter due to uncertainties in the aircraft positions. This again emphasizes that all of these studies suffer from the absence of "true" center positions.

Mean positioning differences between the satellite-based position estimates and the interpolated positions along the aircraft fixes (Fig. 4) are remarkably similar to the satellite-to-satellite differences in Fig. 2. Specifically, the increased scatter in the positions of weaker storm stages is present, which contrasts with the distributions for the NHC estimates in Tables 3 and 4. Three possible explanations are: (i) the aircraft fix uncertainties for weaker storms contribute to some of the

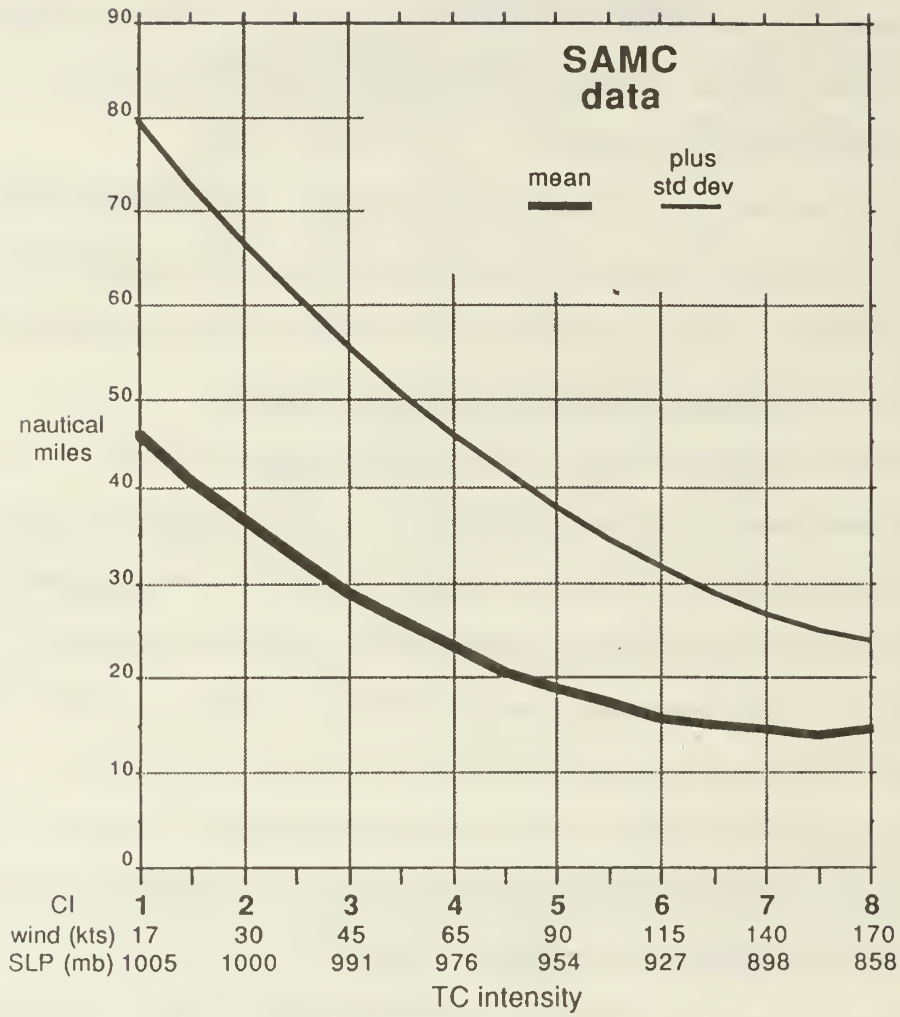

Fig. 4 Mean (heavy solid) plus one standard deviation (solid) of position differences between satellite-based and aircraft reconnaissance observations in western North Pacific as a function of cyclone intensity (Martin 1988).

variability; (ii) that the western North Pacific analysts do not use other intelligence (including aircraft fix information) in the interpretation of the imagery as often as the NHC analysts; and (iii) the animation of the geostationary imagery that has been available only to the NHC analysts contributes significantly to improved positions for tropical storms and tropical depressions. Some evidence for the third factor is the larger deviations in the AFGWC positions from polar orbiter imagery of Atlantic storms (Table 3).

The day and night deviations from aircraft positions (Fig. 5) also depart significantly from the trends in Table 4 for the NHC visible (daytime only) and infrared imagery. Again, it is not possible to establish how these three factors (or other unknown explanations) contribute to these very different results for the weaker storm stages.

3. How does fix accuracy and type affect forecasts?

a. Fix accuracy effects on objective aids

Potential contributions to track forecast errors associated with inaccurate fixes have been estimated by replacing the operational warning positions with the post-storm (best track) positions. This "perfect" position information can contribute to an error reduction in two ways. First, the forecast is originated from the correct position. Second, the initial motion vector is also improved.

Dramatic reductions in short-term forecast errors from the Atlantic CLIPER occur when best track positions are used (Table 5). A 58% reduction relative to the 12-h errors from using

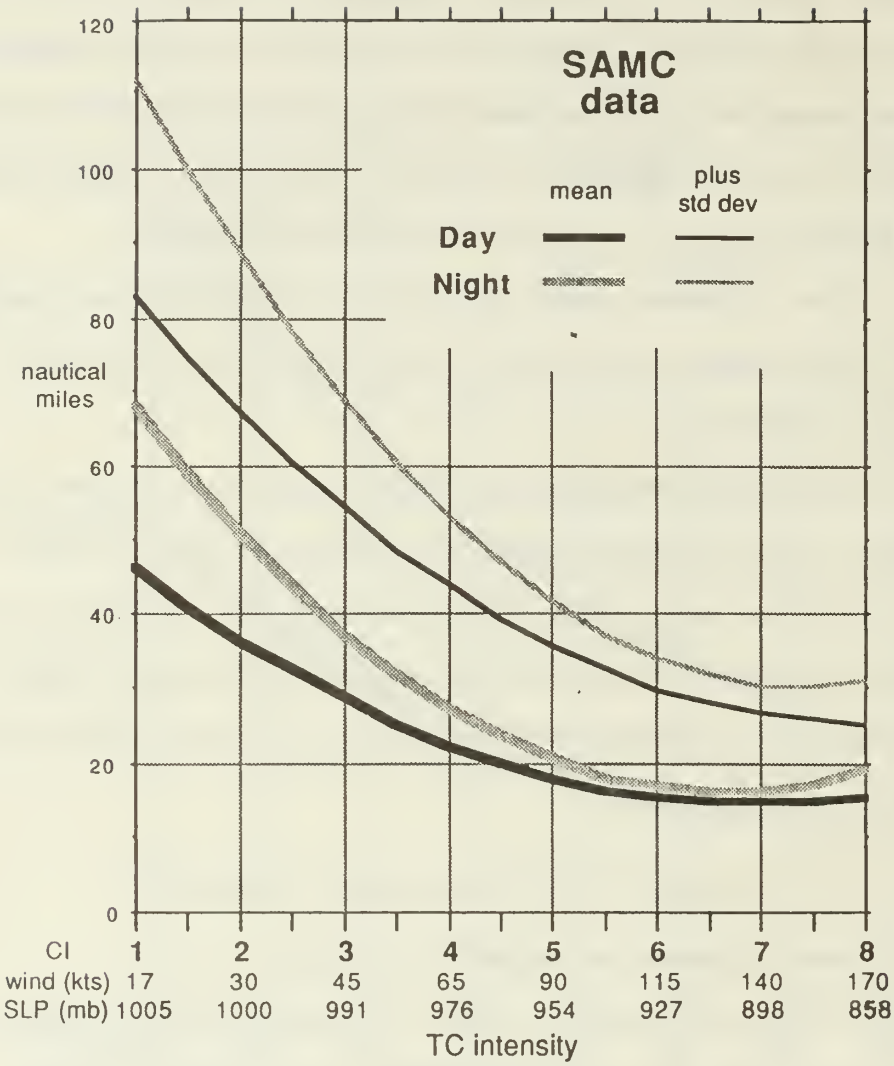

Fig. 5 Mean of day (heavy solid) and night (light solid) plus corresponding standard deviations (thinner lines) of position differences between satellite-based and aircraft reconnaissance observations in western North Pacific as a function of cyclone intensity (Martin 1988).

Table 5 Track forecast errors (n mi) by operational version of CLIPER versus CLIPER with best track positions for Atlantic tropical cyclones during 1972-1987. Percentage improvement from use of best track (BTRK) positions is indicated. Initial positioning errors have not been removed is this comparison (provided by C.J. Neumann).

	Time (h)				
	12	24	36	48	72
Operational errors	65	132	203	275	396
Best track errors	27	87	157	233	371
BTRK Improvement (%)	58	34	23	15	6
Sample Size	1911	1681	1451	1245	902

Table 6 Comparison of the 1984-1985 western Pacific CLIPER track forecast errors (n mi) with warning positions from a working best track using all fixes versus the best track position (extracted from tables provided by M. Fiorino). The format is similar to Table 5, which is for the Atlantic, and uses the NHC verification rules.

	12h	24h	48h	72h
All Fixes	43	102	236	378
Best track errors	39	95	227	369
BTRK Improvement (%)	10	7	4	2
Sample Size	872	872	673	498

operational data is the justification given for intensely observing the storm when short-term predictions are critical, such as during landfall. The best track initial positions produce progressively smaller error reductions with increasing forecast interval. This is reasonable because persistence explains less of the track variance with increasing time as synoptic-scale influences (and probably internal turbulence effects) have more influence.

One of the best objective aids in the Atlantic region is the NHC 83. Neumann (1987) estimated the predictability of this aid by using both best track information and analyzed fields rather than predicted fields. He found that the 12-, 24-, 48- and 72-h forecast errors could theoretically be reduced by 58%, 48%, 47% and 48% respectively. Even though these estimates are also based on perfect predictions (analyses) of the environmental conditions, the similarity of these percentages with the short-term forecast improvements in Table 5 indicate that improved fixes are indeed important for improving track forecasts.

Another test of the impact of fix accuracy on CLIPER forecasts has been made by M. Fiorino (personal communication). A key difference is that Fiorino used an objective procedure to combine the fixes into a working best track. Fiorino's approach mimics the operational procedure at JTWC of updating the past 12- and 24-h positions based on more recent fixes prior to running the CLIPER model. Fiorino states that the CLIPER forecast errors from the objective tracking are about equal to the CLIPER forecast errors from the JTWC warning positions. As shown in

Table 6, the improvement in the western Pacific CLIPER from using best track positions is only about one fifth of the percentages in Table 5 for the Atlantic. This difference comes from Fiorino's use of a working best track, which yields smoothly varying initial motion vectors. Although the NHC "working best track" is also smoothed, it is not as objective or as inflexible as the Fiorino approach. The NHC rationale is that actual changes in the storm track will be reflected earlier than with the more objective technique (R. Sheets, personal communication). Other differences might arise in operations due to the requirement that the NHC forecaster must establish the warning position about 1 h after synoptic time. Nevertheless, Fiorino's results emphasize that differences in procedures of applying the objective aid can lead to different assessments of the impact of fix accuracy.

Fiorino (1985) previously had examined the impact of uncertain initial positions in a dynamical track prediction model by displacing the center one deg. lat. to the north, south, east or west (Fig. 6). The dispersion of the predicted TC positions from these five model integrations was taken as a measure of the error growth due to initial position uncertainty. Contrary to expectations, such large initial errors did not lead to a large dispersion in the future tracks. This result might have been influenced partially by the selection of eastern North Pacific storms for this test, because these storms normally have smooth tracks due to the lack of environmental circulations that contribute to loops, turns, etc. Consequently, the predicted

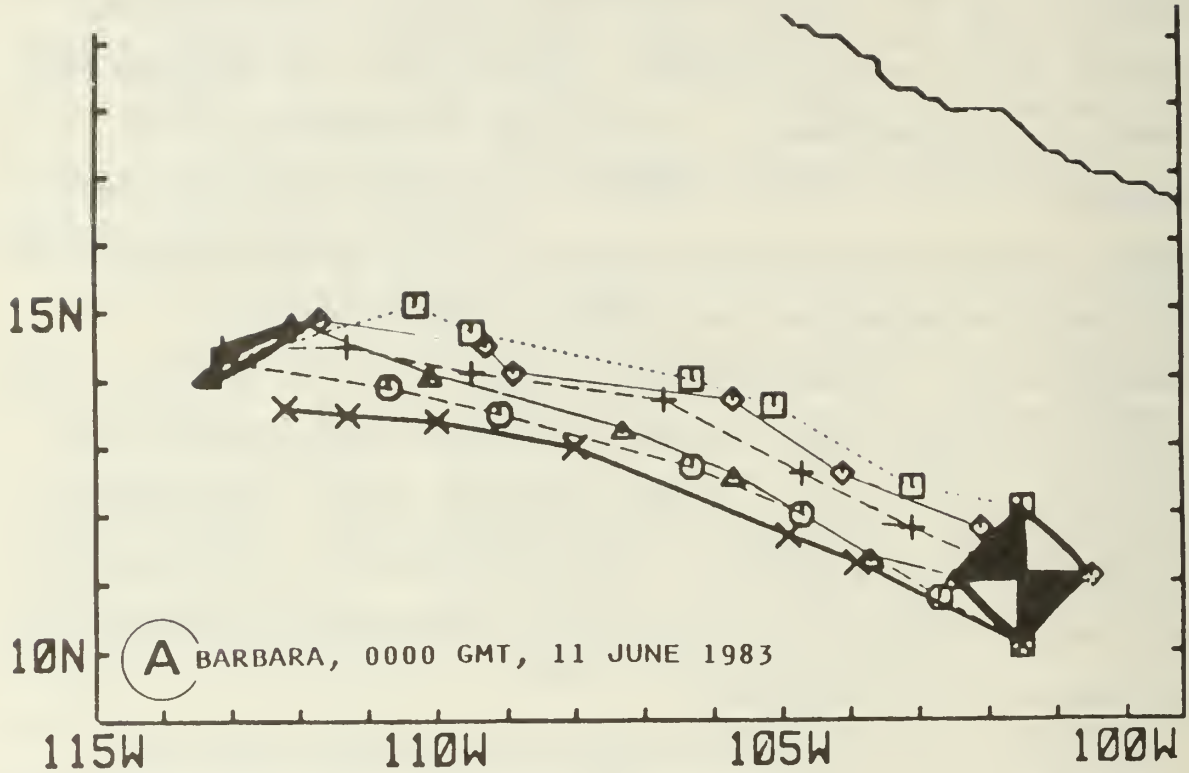

Fig. 6 Track of hurricane Barbara from 00 UTC 11 June 1983 in 12 h intervals (solid with x) and the forecast of the Nested Tropical Cyclone Model (NTCM) from initial positions displaced one deg. lat. to north, south, east and west. The track dispersion due to the initial positions is indicated at the initial time and at 72 h.

tracks from the displaced initial positions tended to parallel the original track, which indicates that the large-scale steering flow in the numerical model has small variations on the scale of the initial position displacements.

DeMaria et al. (1988) have considered the impact of initial position errors in a barotropic forecast model. They include a modification of the initial analyses in the vicinity of the storm to make the initial storm motion match the previous storm motion (pre-processing technique). They also use best track initial positions rather than warning positions as the "control". As in the Fiorino (1985) study, DeMaria et al. also repeat the forecasts with the vortex center displaced 100 km in various directions. However, they maintain the pre-processing technique of adjusting for the previous storm motion persistence. Based on the definitions illustrated schematically in Fig. 7a, the average errors with the displaced vortex centers are shown in Fig. 7b. Although the 100 km initial displacement leads to a significant effect on the average forecast errors at 12 and 24 h, the effect at later times is negligible. The average dispersion D among the four displaced vortex centers remains approximately constant in time. This is not surprising since the pre-processing technique adjusts the surrounding fields to be equal to the previous storm motion and the displaced vortex simply moves parallel to the control position. In this sense, this result is analogous to Fiorino (1985) study, which also had very little variation in the synoptic-scale flow over a distance of 100 km.

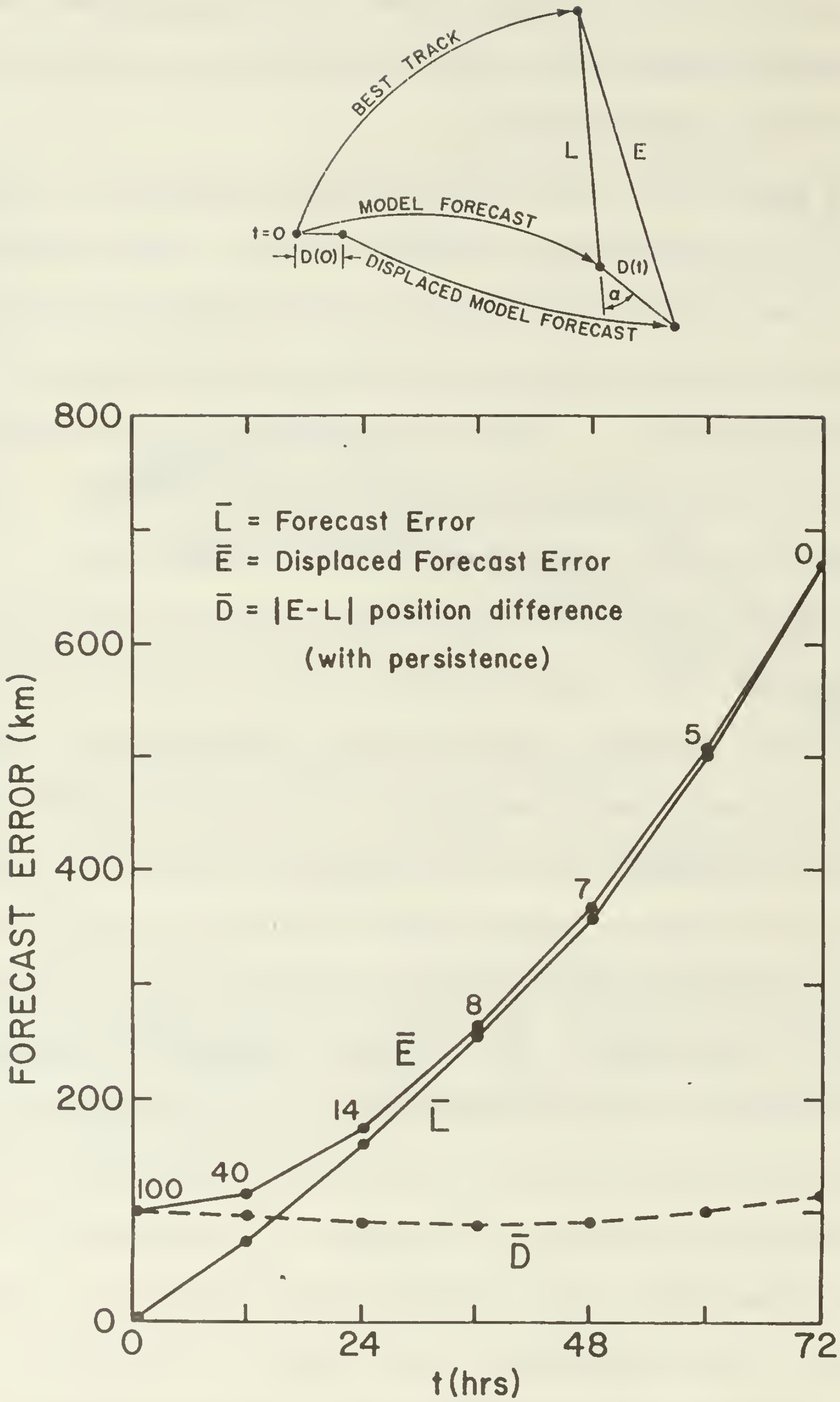

Fig. 7 (a) Schematic of relationships between displacement of initial position and forecast errors for model forecast from control position (L) and from displaced model forecast (E). (b) Time evolution of L, E and D values defined in panel (a) for a series of barotropic model forecasts with persistence motion adjustment from the control and the displaced initial positions (DeMaria et al. 1988).

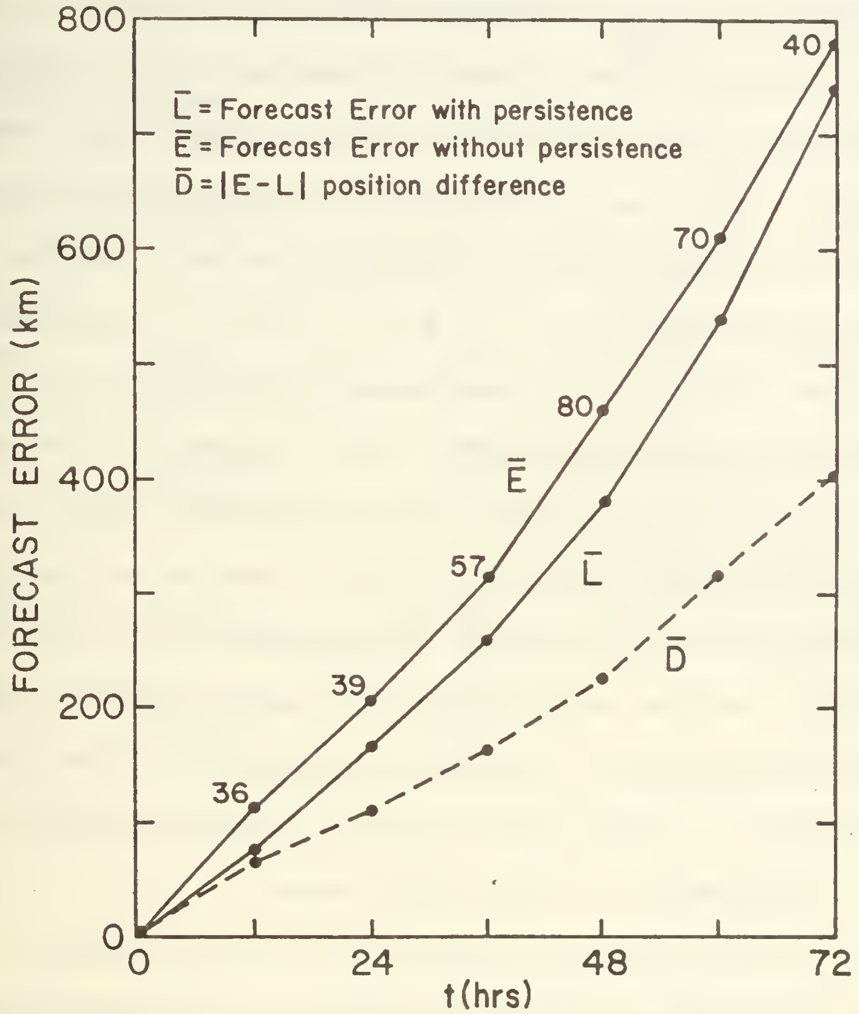

Fig. 8 Time evolution of L, E and D values defined in Fig. 6 for a series of barotropic model forecasts with and without the persistence motion adjustment of the initial fields (DeMaria <u>et al</u>. 1988).

In the above study, DeMaria _et_ _al_. had to specify the previous motion vector to use the pre-processing technique. That is, both the initial position and the initial motion had to be provided. The contribution from the inclusion of persistence of past motion via the pre-processing technique is shown in Fig. 8. The average forecast errors without persistence are consistently larger through the 72-h forecasts, which suggests that the initial motion vector has a much longer lasting effect than the initial position errors in this barotropic model. Notice also that the average dispersion D = | E-L | in Fig. 8 now grows rapidly in time without the pre-processing technique as in Fig. 7b. The 39 error differences after 48 h between the inclusion and the exclusion of the pre-processing technique (Fig. 9) are grouped around the mean value of 80 km. However, one of the 39 cases had differences in forecast displacements of about 1000 km when the initial motion estimate was not used. DeMaria _et_ _al_. conclude that the absence of accurate estimates of the past motion information in the pre-processing technique could lead to significant differences in individual cases.

b. Aircraft reconnaissance effects on objective aids

Martin (1988) demonstrated the effect of having aircraft reconnaissance during the past 12 h on the operational CLIPER forecasts (Table 7). Mean 24-h CLIPER errors were reduced by 6 and 18 n mi for all cyclones and for recurving cyclones respectively compared to those cases for which no aircraft fixes were available during the last 12 h. The 90% differences at 24 h have only slightly larger reductions than these mean CLIPER error

Table 7 Track forecast error (n mi) differences between cases in which an aircraft reconnaissance position was or was not made during the 12 h prior to the forecast. Negative values indicate the forecasts by the CLIPER or OTCM that included aircraft information had smaller errors. Mean and 90th percentile differences are given (Martin 1988).

		CLIPER	OTCM
		24h	
All cases	Mean	-6	-6
	90th %	-5	-9
Recurving	Mean	-18	-5
	90th %	-21	-35
		48h	
All cases	Mean	-3	2
	90th %	28	2
Recurving	Mean	-48	-14
	90th %	-56	0
		72h	
All cases	Mean	15	-6
	90th %	46	18
Recurving	Mean	-46	-47
	90th %	-88	-94

Table 8 Degradation in Western Pacific CLIPER track forecast accuracy (n mi) when aircaft fixes during 1984-1985 were withheld from an objective working best track procedure (M. Fiorino).

	0h	12h	24h	48h	72h
All fixes	14	49	106	239	379
No aircraft	18	53	109	240	381
Difference	30%	7%	3%	---	---

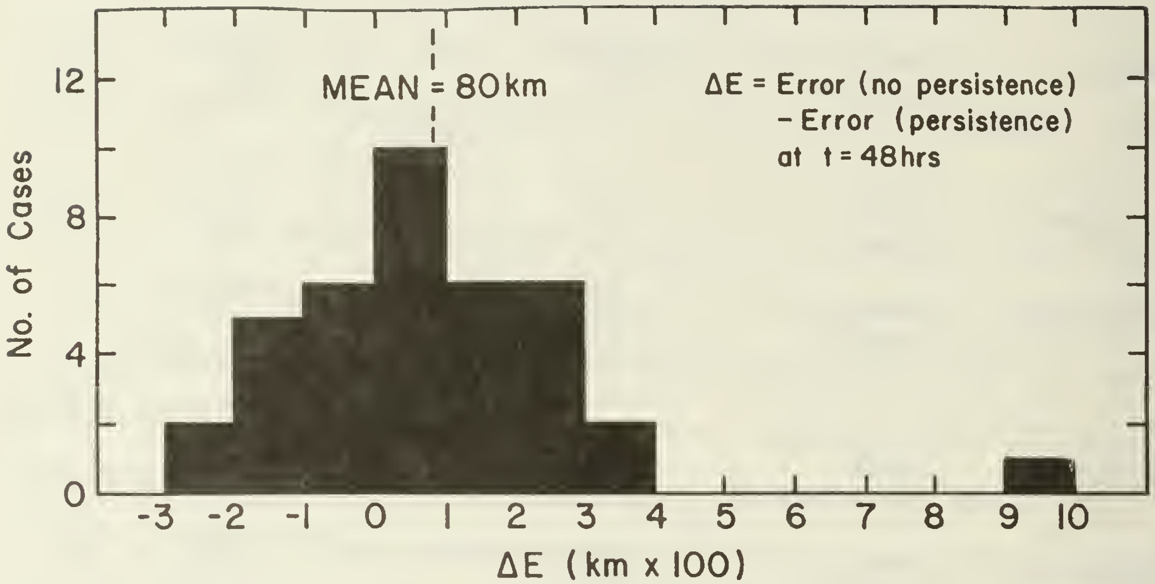

Fig. 9 Differences in 48-h forecast errors between 39 barotropic model simulations with and without the persistence motion adjustment in the initial fields (DeMaria _et al_. 1988).

reductions. The advantage of the aircraft reconnaissance seems to be lost after about 48 h for the mean CLIPER errors of all cyclones, and appears to be a detriment in the mean at 72 h. However, the advantage of having aircraft fixes during the last 12 h persists both in the mean and in the 90% differences for recurving cyclones. Similar trends are found for the One-way Tropical Cyclone Model forecasts, which has consistently been the best objective aid in the western North Pacific. At least in the western North Pacific, the potential reductions from improved initial positions in Table 5 are not achieved by having aircraft reconnaissance during the past 12 h.

M. Fiorino (personal communication) simulated the impact of losing the aircraft fixes using the CLIPER technique. He simply withheld the aircraft fixes from his objective working best track procedure (Table 8). Although the aircraft fixes improve the initial positions by 30% (4 n mi), this contributes little improvement in the 12-h and 24-h CLIPER forecasts. During the 1984 and 1985 seasons that Fiorino examined, the aircraft fixes constituted only 14 and 8 percent of the total number of fixes used by JTWC. Fiorino gives no indication whether these few aircraft fixes are evenly distributed over all of the approximately 900 forecasts (less than one aircraft fix per forecast). Since about 4000 satellite fixes were available during the two years, the average number of satellite fixes per forecast is about 4.5. Redundancy in these satellite fixes can reduce the impact of random errors. Fiorino's study probably underestimates the impact of a good aircraft fix during weak TC situations when the satellite interpretations are ambigious. Nevertheless, Martin's statistics (Table 7) and Fiorino's study indicate that the infrequent aircraft fixes in the western North Pacific were not the primary information for establishing the warning positions in the majority of the situations. Although the satellite fixes have larger errors (see Section 2), the working best track procedure at JTWC blends the numerous satellite fixes into a smooth representation of the TC track for use in the objective aids.

C. Aircraft reconnaissance influence on official forecasts

As indicated above, an aircraft fix is only one piece of information that the forecaster uses in establishing the tropical cyclone warning position and making the track forecast. Consequently, a one-to-one correspondence between an aircraft fix and forecast impact should not be expected.

Martin (1988) compared official JTWC forecast errors when aircraft reconnaissance was available during the previous 12 h versus when reconnaissance was not available. It was somewhat surprising that the sample of weak TC ($V_{max} \leq 45$ kt) showed only a small (9 n mi) reduction in 24-h forecast error, and no improvement in 48-h or 72-h errors when aircraft fixes were available. The only significant impact that Martin could isolate was for recurving TC situations (Fig. 10). The JTWC forecast errors were reduced 18, 21 and 38 n mi at 24, 48 and 72 h respectively when aircraft reconnaissance was available relative to when aircraft fixes were not available during recurvature cases. The 90th percentile errors were reduced 33, 36 and 178 n mi for 24, 48 and 72 h respectively when aircraft reconnaissance was available. Thus, the availability of aircraft fixes seems to have a significant impact on JTWC forecast of recurving storms, which are both dangerous and difficult to forecast.

Sheets (1988) has tabulated the official NHC forecast errors during 1980-87 separately for situations with and without aircraft position data within the prior 6-h period. Neumann (personal communication) has normalized these errors by calculating an expected error based on a corresponding CLIPER forecast plus additional variables such as initial storm intensity and location (Table 9). For example, those official forecasts that had no aircraft reconnaissance available had 12 h errors of 67 n mi, whereas those with at least one aircraft fix had 12 h errors of only 49 n mi. Much of this difference is due simply to the degree of difficulty of these forecasts, since the expected errors would be 65 and 51 n mi, respectively. Consequently, the No Recon forecasts are actually worse by 2%, and the 12-h forecasts with at least one or at least three fixes are improved by 4% and 12% respectively. Similarly, the 24-, 48- and 72-h official errors appear to be systematically smaller with at least one or at least three aircraft fixes (Table 9). Almost all of these improvements are accounted for by the degree of difficulty of these forecasts. Only the forecasts based on three aircraft fixes seem to have sustained improvement relative to the expected errors after 12 h. The 72-h improvement is probably unreliable because the sample size is only 44. The basic conclusion from Table 9 is that the forecast improvement with aircraft is due to a better assessment of the initial motion vector.

In summary, the recent studies of the impact of aircraft fixes on official track forecasts indicate that positive impact occurs if the initial motion vector is improved. Second, the impact in western North Pacific forecasts was in recurving situations, when the track direction is changing. Third, the amount of impact is small when averaged over many storms. It is likely that the impact could be much larger in individual cases, as in the DeMaria et al. study. Sheets (personal communication) feels that perhaps only 10 to 20 percent of the cases may result in major differences from having aircraft reconnaissance. When lives and property are at great risk, the information from aircraft reconnaissance could be crucial. Even if the aircraft fix does not change the forecast, redundant information can contribute to the confidence that the forecaster has in warning the public.

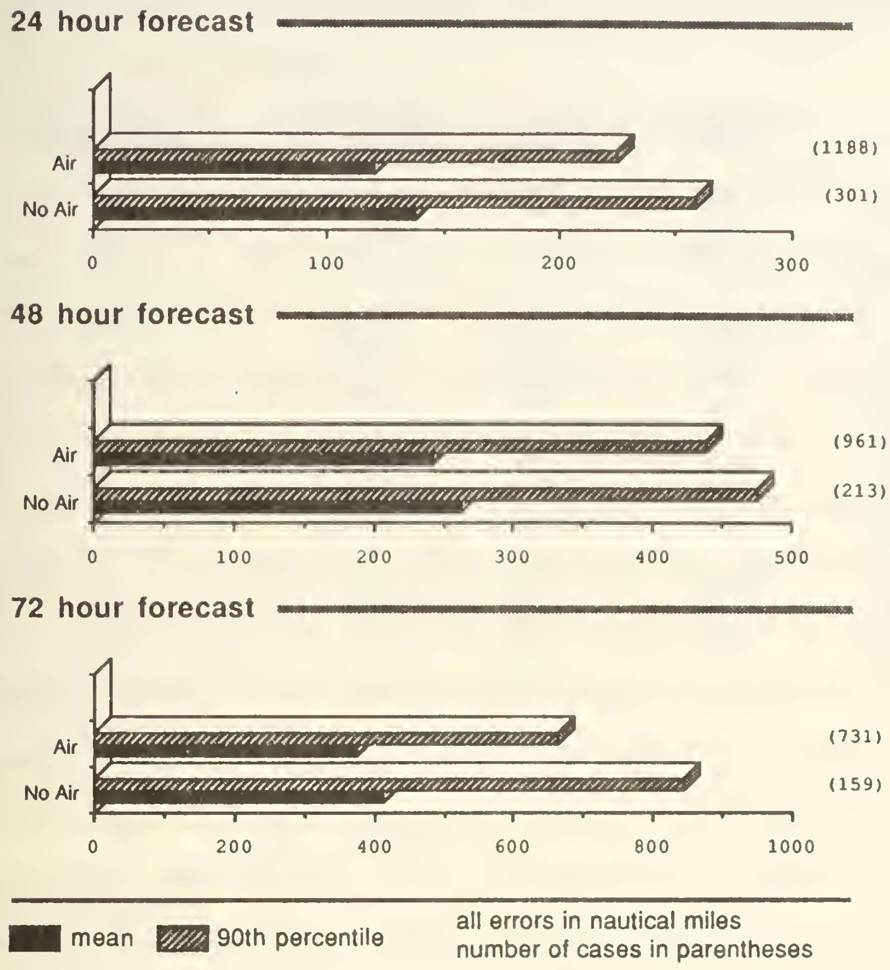

Fig. 10 Official JTWC track forecast errors (n mi) for recurving cases in which aircraft reconnaissance was (AIR) or was not (NO AIR) available during the prior 12 h. Mean (solid) and 90th percentile (stippled) forecasts are given and the same sizes are indicated in parentheses on the right (Martin 1988).

Table 9 Official NHC forecast errors (n mi) during 1980 to 1987 regardless of location. The expected error is determined by normalization of the forecasts through the use of the CLIPER model and the initial storm intensity and location. A negative percent reduction of the expected error relative to the official error indicated the official error exceeds the expected error (provided by C.J. Neumann based on original study by Sheets 1988).

		Sample Size	Error (n mi)	Expected Error	Percent Reduction
12h	No Recon	580	67	65	-2
	≥ 1 Fix	445	49	51	4
	≥ 3 Fixes	115	41	46	12
24h	No Recon	510	130	129	-1
	≥ 1 Fix	393	106	108	1
	≥ 3 Fixes	99	98	102	4
48h	No Recon	369	260	260	0
	≥ 1 Fix	299	229	229	0
	≥ 3 Fixes	73	212	222	5
72h	No Recon	254	397	397	0
	≥ 1 Fix	218	375	375	0
	≥ 3 Fixes	44	289	330	12

4. Conclusions

The loss of aircraft reconnaissance for western North Pacific tropical cyclones has led to a number of studies of the impact of various observational platforms on tropical cyclone positioning and fixing.

(i) The accuracy of satellite positions of TC are a function of storm intensity, with larger errors for weaker, ill-defined storms. The gridding of the satellite images has improved during the past 15 y. If this gridding is done carefully, the accuracy of the gridding should contribute less than 6 n mi to the position uncertainty, which is equal or less than the quantification error in recording the position (nearest 0.1^{o} lat.). A number of satellite analysts examining the same imagery will disagree as to the TC center, with the dispersion among the position estimates increasing with decreasing storm intensity (Mayfield et al. 1988; Martin 1988; Guard 1988). The study by Guard (1988) suggests that inexperience of the satellite analyst may contribute to the dispersion. Perhaps the most important conclusion is that the satellite analyst needs to provide a measure of that position uncertainty from the available imagery so that the forecaster can properly interpret the information.

(ii) The dispersion of position estimates in the controlled experiments described above (in which the analyst was provided only a particular type of satellite imagery) emphasizes the importance of not having the operational analyst work in such isolated conditions! The analyst should have available other types of imagery (visual, infrared, enhanced infrared, microwave, water vapor channel). Similarly, the analyst should have available other synoptic or reconnaissance information to assist in the interpretation, especially in weaker storm situations when the uncertainty is largest. This information should include the current or recent past positions from analysts at other locations since more than one analyst examining the same imagery is helpful. Last but not least, the lines of communication between the analyst and the forecaster should be open. The emphasis throughout should be on quality control of the information to provide the best possible guidance to the forecaster and to the public.

(iii) The forecaster must consider carefully the uncertainty in the fix information during the positioning of the TC. Understanding the dispersion in the satellite and other fix information allows the forecaster to draw a smooth track that represents the motion of the overall TC, and avoids following some short-term oscillation in the center or some unrepresentative center fix. Conservative operating procedures that establish the TC position over a series of past fixes are important. Extrapolation of future positions based on recent fix information should be avoided.

(iv) The analysis of the fix information provides estimates of both the present position and the recent storm motion. Some statistical techniques make good use of the initial storm vector. Recent studies with a barotropic model also indicate that information on recent storm motion can be incorporated via pre-processing techniques that adjust the initial fields to improve the short-term forecasts. When pre-processing is incorporated, the dispersion in track forecasts beyond 24 h in these barotropic models is rather small. This indicates that the initial fields in the barotropic models represent only large-scale variability and are not very sensitive to initial position error.

(v) The objective aids are most sensitive to initial position error during the 12-24 h forecast intervals. At least in the average for large sample sizes, the forecasts by these aids do not show significant impacts beyond 36 h. However, large errors do occasionally occur as a result of initial position uncertainty. Since this is most likely to occur when the future track is at a bifurcation in the field, the forecaster needs to be more alert to initial position uncertainty in these situations. One clue to this situation may be when the suite of objective aids provides widely scattered future tracks.

(vi) Aircraft position fixes appear to have the largest positive impact on official track forecasts during recurvature situations (latitude band 20° to 35°N). Multiple aircraft fixes seem to be beneficial, perhaps through increasing the confidence of the forecaster in the TC position. The consistency/scatter in the fixes also provides a basis for evaluating the reasonableness of the initial storm motion vector. The aircraft observations during the flight to and from the storm probably also contribute valuable information to the forecaster. However, this impact is more difficult to assess.

(vii) Much of the attention in the recent studies has been on the track forecast problem. The intensity forecast uncertainty has also important implications in the warning process. Evacuations of coastal residents depend on the expected rise in water level as well as the possible damage to buildings or other sturctures from the wind. In cities such as Galveston TX, New Orleans LO, Ft. Myers FL, Miami FL, Charleston SC and Atlantic City NJ, the maximum water rise and the extent of land inundation increases markedly for a Category III (111-130 mph) versus a Category II (96-110 mph) storm (R.L. Sheets, personal communication). This could mean the difference between evacuations of 100,000 to 1,000,000 people. The credibility that the forecaster has with the public could be damaged with overwarning or underwarning of these coastal residents. Thus, the wind structure forecast of landfalling hurricanes near major cities has great potential impact, and various observational tools must be utilized to improve these forecasts.

The meteorological aspects of the impact of aircraft or other fixes in the TC is only one factor in the problem. Economics, societal impacts from an inaccurate forecast, and other factors also need to be considered. Of course, the forecaster would like to have the most information possible and desires seemingly redundant observing systems so that he/she can make the best decision during the critical forecast situations. It is true that meteorologists are more remembered for their errors (failures) than for their successes. More importantly, the forecaster knows people may be hurt or killed and property may be lost or damaged unnecessarily during these critical tropical cyclone situations.

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